

# Cosmic GRB energy-redshift relation and Primordial flares as possible energy source for the central engine

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## Abstract

By considering similar observed properties of gamma ray bursts (GRB) and solar flares with the prevailing physical conditions in the cosmic environment, the following study suggests that most likely and promising energy source for the central engine which triggers GRB may be due to primordial flares, solar flare like phenomena, at the sites of inter galactic or inter galactic clusters in the early universe. The derived energy-redshift relation ,  $E = E_0(1+z)^3$  (where  $E$  is the amount of energy released,  $z$  is the redshift of GRB and  $E_0$  is a constant which is estimated to be  $\sim 10^{52}$  ergs ), from the simple flare mechanism, is confirmed from the least square fit with the observed energy-redshift relation. Some of the physical parameters like length scale, strength of magnetic field, *etc.*, of the flaring region of the GRB are estimated.

## 1 Introduction

Since the discovery of GRB, the source of the central engine which triggers this phenomenon remains elusive till today. To date, there are more than hundred theoretical models on GRB ( see the bibliography web site, <http://ssl.berkeley.edu/ipn3/index.html>, compiled by Hurley). Based on the insufficient data, in the initial period of observations, many models on GRB favored energy source of galactic origin. However, recent observations are not consistent with these models and the models which explain that source of GRB could be of extragalactic origin are most favorable (Piran 1999). Though, these models can explain some of the observed phenomena, other outstanding observed properties such as energy source of the central engine and isotropic distribution of the GRB in the universe remain to be explained.

Presently there are two main schools of thoughts on the central engine of the GRB : (i) neutron star-neutron star ( or neutron star -black hole) binary mergers and, (ii) hypernovae. Though very few of the observations appear to favor these models, they have the following difficulties (McLaughlin *et al.* 2002). (a) The small spatial offsets between GRB counterparts & their host galaxies (Bloom, Kulkarni & Djorgovski 2002) are hard to reconcile with the merging neutron stars which supposed to have large offsets from the center of the host galaxy. (b) Though there appears to be a strong association between the GRBs and the star formation rates, collapsar (hypernovae) model has the following difficulties. An emission line has been found (Antonelli, et al. 2000; Piro et al. 2000) in some x-ray afterglows of the gamma ray bursts (GRB) whose energy is roughly consistent with Fe K $\alpha$  at the redshift of the host. This is clearly against the hypernovae model, since hypernovae (supernovae) primarily produce nickel (Woosley & Weaver 1995), not iron. Even if one believes that hypernovae models explain the source of central engine, it is not clear to us that such a large-scale phenomena accrete material onto a black hole and form GRB events on the time scales of few seconds to minutes. Hence, some other physical phenomenon may be responsible for the central engine which triggers GRB events. It is found from this investigation that, primordial flares (in the regions of inter galactic or inter galactic clusters), *i.e.*, solar flare like phenomena in the early history of the universe, may be most promising energy source for the creation of GRB. Though similar studies (Qu & Wang 1977; Stecker and Frost 1973; Vahia and Rao 1988) indicate relevance of stellar flares as the energy source of GRB, the observed spectra of GRB imply that GRB must be of extragalactic origin and hence it is unlikely that stellar flares may be energy source for the cosmic GRB.

Previous studies (Stecker & Frost 1973; Vahia and Rao 1988) show many similar observed properties between the solar flare like phenomenon and the GRB event like phenomenon. We add following additional similarities of GRB events with the solar flares : (i) the source size is compact, (ii) time scales is  $\sim$  seconds to minutes, (iii) radiation is observed in most of the electromagnetic spectrum, (iv) non-thermal energy spectrum and (v) polarization  $< 30\%$ . It is also interesting to note that emission line around 5 keV in GRB000214 is almost similar to the emission line at 5 keV in solar x-ray flare (Zirin 1988) which along with the ideas presented in our paper give much credence that GRB events may be solar flare like phenomenon in the cosmic environment on larger scales. From the observed similar properties of the

neighborhood solar flares and the distant cosmic GRBs and, the following energy-redshift relation derived from the physics of flare phenomenon, we propose in the present study that the central engine which triggers cosmic GRB transient events may be solar flare like phenomenon on larger scale in the early history of the universe. During that epoch the universe was very active and the first stars and effectively galaxies were either begin to form or might have formed (Larson 1999).

Presently it is believed (Priest 1981; Haisch & Strong 1991; Parker 1994) that the source of energy produced in the solar flares is due to phenomenon called *magnetic reconnection* in a very compact region wherein oppositely directed magnetic flux, in the limit of finite electric conductivity, annihilate each other and releasing required amount of flare energy with the acceleration of highly energetic particles (Lenters & Miller 1998; Tsuneta and Naito 1998). In the following we give a brief introduction of theory of magnetic reconnection invoked for the study of the solar flares.

## 2 Magnetic reconnection and Primordial Flares

Let oppositely directed magnetic flux of large length scale  $L$  are merged with inflow velocity  $v_{in}$ . This merging of flux will form a current sheath of thickness  $\delta$ . Then the law of magnetic induction according to MHD description is

$$\frac{\partial B}{\partial t} = \text{curl}(v \times B) + \eta \nabla^2 B, \quad (1)$$

where  $B$  is strength of the magnetic field,  $v$  is the velocity and  $\eta$  is the magnetic diffusivity of the plasma. The first term in the above equation is due to convective flow and second term represents the magnetic diffusion of the plasma. Outside the region of reconnection, magnetic diffusivity is very low and magnetic field is glued to the plasma and moves along with the plasma. That is magnetic field is frozen to the plasma. This condition of infinite electric conductivity fails in the region of magnetic field reconnection by producing very high gradients of currents and electric fields. Dissipation of these strong currents leads to annihilation of magnetic field in the region of magnetic reconnection where steady state exists so that convective and resistive terms in equation (1) are equal. The amount of energy released by the annihilation of magnetic field  $B$  and cube of length  $L$  is estimated to be

$\sim L^3 B^2$ . The ratio of convective to resistive term called "magnetic Reynolds number" is given as follows

$$R_m = \frac{v_{in} \delta}{\eta}, \quad (2)$$

where  $\delta$  is the thickness of reconnection region. The assumption of incompressibility and conservation of flux yields

$$v_{out} = \frac{L}{\delta} v_{in} = v_a, \quad (3)$$

where  $v_{out}$  is out flow velocity,  $v_{in}$  is the inflow velocity and,  $v_a$  is the ambient Alfvén wave velocity whose perturbations are perpendicular to the field line and travel along it.

Outside the region of magnetic reconnection, the convective term in equation (1) dominates over the resistive term. That is  $R_m \gg 1$  and hence the electric field is non-dissipative. However, inside the layer of thickness  $\delta$ ,  $R_m \ll 1$  and, the electric field  $E = \eta J$  is dissipative which leads to domination of kinetic effects. For example, two dimensional simulations (Brown 1999) indicate that magnetic flux and electron flow decouple in the accelerating region resulting in acceleration of electron beams by ejecting with super-Alfvénic velocity.

## 2.1 Primordial Flares

Primordial flares means that flares of extragalactic origin when the universe was in the nascent stage with high magnetic activity like the sun's atmosphere. We expect the flares to occur in the optically thin medium situated either in the regions of inter galactic or inter galactic clusters. The length scales are of cosmic dimension and, flares of extragalactic origin are produced by the oppositely directed magnetic flux due to peculiar motion of cosmic bodies such as galaxies or cluster of galaxies or near the sites of supernova ejections from the galaxy. The region of magnetic reconnection is assumed to be formed by merging of oppositely directed magnetic field which is of primordial origin. The typical observed peculiar velocity fields of galaxies are  $\sim 10^7$  cm/sec and length scales of magnetic elements  $\sim 10^{24}$  cms (Giovaneli 1998). It is expected that in order to reproduce the observed magnetic fields  $\sim \mu$  G in galaxies, galaxy clusters and inter galactic clusters (Kroneberg

1994; Vallee *et al.* 1987; Lesch and Chiba 1997; Bagchi 1988; Taylor and Perley 1993), a primordial field of  $\sim 10^{-9}$  G is required.

Based on the simple flare model described in §2 and available observed informations on GRB, in the following, first we derive the GRB energy-redshift relation and compare with the observed energy-redshift values. From the linear least square fit to the observed data, we estimate the average energy liberated from the GRB events. we also estimate size, strength of the magnetic field and thickness of the reconnection layer at the site of GRB formation. Using this information and conservation of mass and flux, we estimate strength of the magnetic field of the region at the present epoch ( $z = 0$ ). Then we compare estimated strength of magnetic field and velocity of outflow  $v_{out}$  from the site of flare region with the strength of the observed large-scale magnetic field and peculiar velocity of the galaxies.

### 3 GRB Energy-Redshift Relation

We know that the amount of energy released by annihilation of magnetic field of strength  $B$  and cube of length scale  $L$  is  $E \sim L^3 B^2$ . We assume that in the early universe, on the average, large-scale currents are zero. This implies that currents  $J = \text{curl} \mathbf{B} = 0$ , where  $\mathbf{B}$  is the magnetic field. This relation leads to the potential fields and hence a dipole field like structure is the likely dominant mode which still may be existing in the cosmic environment. Dipole field like structure varies as  $\sim L^{-3}$ , where  $L$  is comoving length at the time of emission. Apply the redshift correction, then comoving length  $L$  is related to length scale  $L_0$  at the present epoch as  $L_0 = L(1 + z)$ . Next plug in this relation in the energy  $E$  ( $\sim L^3 B^2$ ) and from the conservation of magnetic flux, we get the following relation

$$E = E_0(1 + z)^3. \quad (4)$$

Here  $z$  is the redshift of the GRB events and  $E_0$  is constant of energy to be determined from the observed data. This relation implies that *the energetics of the GRB events is approximately directly proportional to the cube of their redshift values*. This means the GRB events appear to be more energetic in the early universe compared to the universe which has small  $z$  values.

In order to check validity of thus derived GRB energy-redshift relation, we fit a general relation  $E = E_0(1 + z)^M$ , where  $E_0$  (ergs) and  $M$  are constants

to be determined from the least square fit of the observed energy and redshift data. By linearizing the general form, we obtain the relation  $Y = C + MX$ , where  $Y = \log(E)$ ,  $X = \log(z + 1)$ ,  $C = \log(E_0)$ . We choose 12 GRB events which have known energy and redshift values available from the web site <http://www.aip.de/~jcgr/grbrsh.html>. After subjecting to the least square fit to the observed data, we found the constant coefficients to be  $C = 51.6$  which implies  $E_0 = 10^{51.6}$  ergs,  $M = 3.05$  and significance of the  $\chi^2$  value is  $> 99\%$ . Basically  $\chi^2$  ( $= \sum_i [(N_i - n_i)^2 / n_i]$ , where  $N_i$  is the number of events observed in  $i$ th bin, and  $n_i$  is the number of expected events) value tests how our computed energy values agree with the observed energy distribution of GRBs. It is to be noted that in order to compute the  $\chi^2$ , uncertainties in the data is not necessary. Since uncertainties are presently not available in the observationally determined redshift values, we could not determine the uncertainties in the determined parameters  $C$  and  $M$  respectively. On the other hand, if sufficient data is available, one can determine the uncertainties from the property of the standard deviations determined from the observed data (Press *et al.* 1992). In Fig 1., we illustrate the GRB energy-redshift relationship. The observed energy values are denoted by signs of star and continuous line is a linear least square fit to the data. It is crucial to be noted that the coefficient,  $M = 3.05$ , determined from the fit of the empirical data is very close to coefficient  $M = 3.0$ , according to our expectation that *primordial flares may be the energy sources of the central engine* which trigger GRB events.

Owing to a very small data sample of the observed  $\log(\text{energy})$ - $\log(z+1)$  data, we obtained a nominal but significant value of the correlation coefficient ( $\sim 50\%$ ) in our analysis. In fact one may argue that finding a luminosity that rises with distance shouldn't be surprising for a flux limited sample. However, from the following analysis using large sample of Fenimore & Ramirez-Ruiz (astroph-0004176) luminosity data, such a statistically significant  $\log(\text{energy})$ - $\log(z+1)$  relationship exists. In any case, one may argue that, the redshift uncertainties are usually either extremely small, or the redshifts in the literature are a lower limit on the true redshift (for some absorption redshifts). In order to avoid such doubts from the reader's mind, we enhanced the reliability of the statistics in the following way.

We consider a large sample of the redshift-energy data from the time variability of the GRBs obtained from Fenimore & Ramirez-Ruiz (astroph-0004176). For our analysis, we chose such a sample ( $z$  values in the steps of

0.1) of 42  $\log(\text{energy})-\log(z+1)$  values ( Fenimore and Ramirez-Ruiz astro-ph0004176) and fitted with the generalized law  $E = E_0(1+z)^M$ . More data enabled us to estimate the uncertainties in the following parameters :  $E_0 = 10^{50.6 \pm 0.27}$ ,  $M = 3.01 \pm 0.31$ , coefficient of correlation 90% and significance of  $\chi^2$  value is  $> 99\%$ . Though the values of  $E_0$  determined from both the fits appear to be different, in near future, as we collect more observations of energy-redshift data, both the values of  $E_0$  come closer. In Fig 2., we illustrate the inferred energy-redshift relationship. Note that value of the index  $M$  determined from the observed energy-redshift data and inferred energy-redshift data is same. This extra analysis of least-square fitting shows that our proposed conjecture ( "the energy-red shift relation obtained from the simple flare mechanism is similar to the observed energy-redshift relation") is right.

## 4 Estimation of Physical parameters of the GRB

The observations show that the time scales of GRB phenomena vary from  $10^{-3}$  sec to  $10^3$  sec. For the known redshift of GRBs, we find that average time scale is  $\sim 100$  sec. By constraining that out flow velocity in the current sheet should not exceed the velocity of light and in order to produce average energy  $E_0 \sim 10^{52}$  ergs, the length  $L$  of the cube should be  $\sim 10^{12}$  cms and field strength in the reconnection region to be  $\sim 10^8$  G. It is crucial to be noted that the estimated field strength is close to the strength of magnetic field inferred from the observations (Piran 1999) of GRB spectrum in absorption lines. If we assume  $L = \delta$ , then from equation (3), this implies that  $v_{in} = v_{out} = v_a$ . Thus from the constrained outflow velocity ( $10^{10}$  cm/sec) which is also equal to Alfven velocity,  $v_a$ , and from inferred strength of the magnetic field, density of the reconnection region is found to be  $\sim 10^{-5} \text{ g/cm}^{-3}$ .

Let us now reverse back from the phase of the early universe, using inferred length scale and strength of magnetic field in region of reconnection, and ask what could be the strength of magnetic field at the present epoch (  $z = 0$ ) that might have been distributed over large length scales. If so, does it match with strength of the observed large-scale magnetic fields in the

universe. Conservation of flux leads to a relation

$$B_0 = B_{present} \frac{L^2}{R_0^2}, \quad (5)$$

where  $B_0$  and  $R_0$  are strength and length scale of the magnetic field at the present epoch ( $z = 0$ ),  $B_{present}$  and  $L$  are strength and length scale of magnetic field in the reconnection region in the earlier epochs. If we take the observed large-scale magnetic field which have typical length scales  $R_0 \sim 10 \text{ kpc} \sim 10^{22} \text{ cm}$ , we get  $B_0 \sim 10^{-12} \text{ G}$  which is almost similar to the expected field strength of primordial origin at the present epoch. Hence the typical rate of GRB is expected to be  $\sim R_0/v_{in} \sim 10^5$  years which is very close to the observed rate of GRB  $\sim 10^6$  years.

## 5 Conclusions and discussion

Our conclusions of this study are as follows :

By considering the similar observed properties of GRB and solar flares, it is proposed that the energy source of the gamma ray bursts of extragalactic origin is similar to the energy source which triggers solar and stellar transient activity phenomena like flares. From the simple theory of flare mechanism, we derived the energy-redshift relation and compared with the distribution of observed energy and redshift values. From the linear least square fit, with a high significance of  $\chi^2$  value, it is found that the derived flare energy-redshift relation very well matches with the observed energy and redshift relation confirming that *most likely and promising energy source for the central engine which triggers GRB phenomena may be due to primordial flares, similar to solar flare like phenomena, which might have occurred in the early universe.* From the least square fit, we estimated the average energy  $E_0$  of the GRB events to be  $\sim 10^{52}$  ergs and inferred the physical parameters of the flaring region. The inferred results indicate that the source region requires length scale of  $\sim 10^{12} \text{ cms}$ , strength of the annihilating magnetic field  $\sim 10^8 \text{ G}$  and the outflow velocity of the plasma may be  $\sim 10^{10} \text{ cm/sec}$  if we assume that thickness is equal to length scale of the reconnection region. By the theory of conventional flare mechanism and conservation of mass, we also estimated density of the reconnection region to be  $\sim 10^{-5} \text{ gram cm}^{-3}$ . Finally, by taking the observed typical length scale of the cosmic environment at the



present epoch ( $z = 0$ ) and conservation of magnetic flux, we estimated the strength of the primordial magnetic field which is almost similar to expected strength of the magnetic field of primordial origin. Lastly, we estimated typical rate of GRB per galaxy to be  $\sim 10^5$  yrs.

In this study, we inferred from flare theory that in order to get the required observed GRB energy, length scale of source region may be  $\sim 10^{12}$  cms and strength of the magnetic field  $\sim 10^8$  G. The difficulty here is how to annihilate such a large scale region within few seconds. The answer lies in the instabilities (Hood 1986) created by attaining such a structure of the magnetic fields. Once instability starts, reconnection starts with in few seconds, accelerate the particles very close to velocity of light and shock structures would be formed which follows the creation of non-thermal spectrum.

One may get the following doubts : (i) the model no longer explains why essentially all well-localized GRBs are found in the stellar field galaxies, (ii) the model doesn't explain any of the apparent evidence for links between actively star-forming regions and GRBs and (iii) the model doesn't explain any of the rich phenomenology of long-lasting GRB afterglows. For all these questions, we have following answers. We can not say that essentially all well-localized GRBs are found in the stellar field galaxies. As explained in the introduction, in fact, there are small offsets between GRB counter parts and their host galaxies. Moreover, recent analysis (Schaefer, 1999; Band, Hartmann and Shaefer 1999; Mirabal, *et al.*, 2002) disfavor GRB events associated with the star-forming regions where one would expect optically thick medium. That means the optically thin environment like the sun's atmosphere is essential for the GRB production. Infact the studies (Schaefer, 1999; Band, Hartmann and Shaefer 1999) suggest one of the possibilities that GRBs might reside in the inter galactic space which we also propose as the probable site for the GRB origin. As for the second doubt, it is only apparent evidence and not all the observed GRBs are in star-forming regions. Incase, we assume that stars in the early universe are at extragalactic distances then GRB events should be correlated with history of the star formation. This may be true upto  $z < 2.5$  but it is not true for  $z > 2.5$  (Ruiz, *et al.*, 2002). Hence, it is more likely that GRB events might have occurred in the back ground of the host galaxy which has star-forming region. It is also not ruled out that it may be mere coincidence with the GRB events that might have occurred in the star-forming regions of the host galaxy. Right now, we can

not answer the last question, because aim of the present study is to reveal the source and explain the physics behind the central engine of the GRB.

It is known from solar flare observations that before eruption of the flare, gradients of magnetic fields occur over the solar surface. It would be interesting to get observational information regarding development of any such strong gradients of magnetic fields (inferred from the Faraday polarization data in radio domain), at the site of GRB flare, before it's eruption. In the present study we phenomenologically modeled GRB as a primordial flare phenomenon. However, detailed solution of MHD equations in the environment of the early universe is essential in order to understand the GRB phenomenon completely.

*The most important finding from the present study is that the energy-redshift relation obtained from the simple flare mechanism is similar to the observed energy-redshift relation which will help in finding the unknown redshifts of other observed GRB events.*

In summary, this study indicates that solar like transient MHD phenomena, especially primordial flares in the inter galactic or inter galaxy cluster region, may be most promising energy source for central engine which triggers the GRB events. Though most of the observed properties of GRB phenomena and solar flare phenomena are similar, additional observational informations such as signature of the gradients in the extragalactic magnetic fields at the site of production of GRB is required in order to prove our proposed conjectures in this study.

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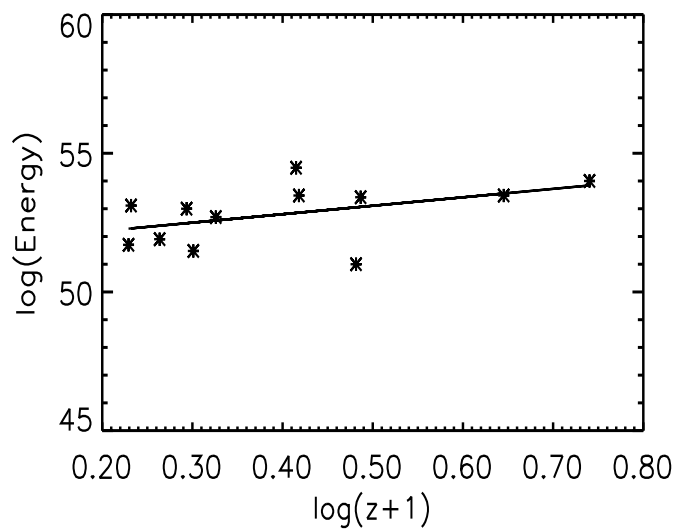


Figure 1: The cosmic GRB energy versus redshift values in the logarithmic scale. The observed values are denoted by signs of star and continuous line is a linear least square fit of the form  $Y = C + MX$ , where  $Y = \log(\text{energy})$ ,  $X = \log(z + 1)$  and  $z$  is the redshift, to the observed data.

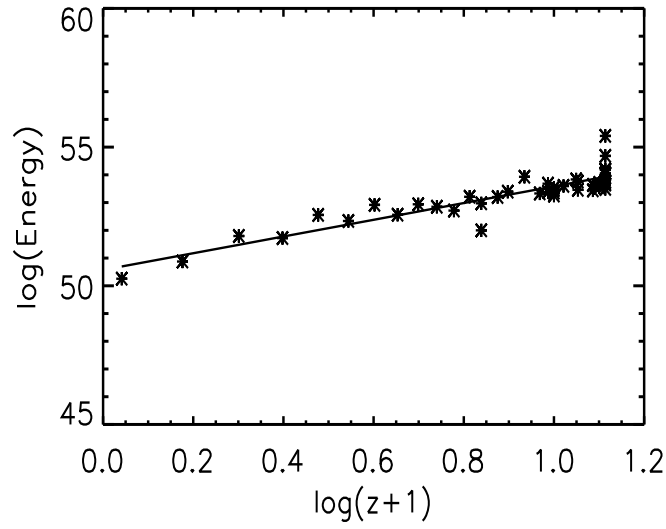


Figure 2: The cosmic GRB energy versus redshift values in the logarithmic scale. The inferred values (taken from Fennimore and Ramirez-Ruiz, 2000) are denoted by signs of star and continuous line is a linear least square fit of the form  $Y = C + MX$ , where  $Y = \log(\text{energy})$ ,  $X = \log(z + 1)$  and  $z$  is the redshift, to the observed data.